

APPLICATIONS OF A DIGITAL ACOUSTIC-EMISSION DATA-ACQUISITION WORKSTATION

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An eight-channel, data-acquisition system is used to acquire and analyze acoustic-emission [AE] data from aluminum surface-crack specimens. The system is calibrated using known source locations and laser-generated ultrasound to determine the transducer locations by finding the arrival time of the longitudinal wave and then doing a nonlinear, least-squares fit. From these transducer locations, the origin of AE sources can be determined using a similar procedure. Automated methods for determining source location by finding the first signal above noise on each channel and identifying this signal as the longitudinal wave arrival are developed for processing the vast amount of data generated during a typical experiment. The application of these methods to data acquired during tensile testing is discussed.

A goal of this research is to sense acoustic events to enable the prediction of conditions for initiation of crack growth. The predictions will be based on models being developed by Parks and McClintock [1] that calculate the effects of specific crack growth conditions. These models require detailed information about the location of the crack initiation sites and about the types of crack growth for various material properties and geometric conditions. The development and verification of these models are closely tied to fracture mechanics experiments being performed at the Idaho National Engineering Laboratory (INEL). The experimental program will point the direction for development of the models and can then be used to confirm the predictions using the source location and source identification methods described in this paper. The source location tells where to conduct metallographic examinations so the extent of cracking can be identified. Then, the actual conditions for the real materials around the crack border can be compared to predicted and assumed conditions in the model.

DIGITAL AE WORKSTATION

The current AE detection system is an expanded and faster version of the system described in Reference 3. As currently configured, the system can digitally acquire signals on up to eight channels. Once armed, the system constantly digitizes the output of all active channels until the receipt of a "stop" trigger, generated when the signal level in a reference channel crosses a predetermined threshold. After receipt of the stop trigger, a specified number of pre- and post-trigger samples are

transferred to computer memory and the system is cycled and armed for the next event. A typical dead time is 70 ms for an eight-channel setup collecting 640 points of data per channel.

SOURCE LOCATION CALIBRATION

The ability of the workstation to establish the source location is determined by the precision of the transducer positions, the sampling rate, and the transducer bandwidth. The transducer positions are determined by using a focused laser beam to simulate broadband AE events in precisely controlled locations. Using the arrival times of the longitudinal waves at each transducer and the known location and time of the source, the transducer positions can be determined using a nonlinear least-squares fit.

Eight transducers are attached to a 12.83 mm thick aluminum surface-crack specimen as shown in Fig. 1. The transducers are positioned on either side of the crack and on both the front and back surfaces of the specimen. The transducers are in these same positions during the tensile test described below. A Nd-YAG laser beam is then used to generate simulated AE signals on the back surface of the specimen along a line in the plane of the precrack, ranging about 10 mm on each side of the center of the crack. Forty-seven data sets are collected with a spacing of either 0.4 or 0.04 mm between laser spot positions. In this experiment, the gain of the system was deliberately turned up so that the arrival of the longitudinal wave (the first signal in the data) can be clearly identified.

Since the path length between the source and transducer is a function of the source location, the signals detected in each channel show differing time delays. The time for a stress wave to travel from the source at (x_o, y_o, z_o) to a transducer located at (x_A, y_A, z_A) is

$$T_A = [(x_o - x_A)^2 + (y_o - y_A)^2 + (z_o - z_A)^2]^{1/2}/c \quad (1)$$

where c is the longitudinal wave speed. In the calibration experiments the system is triggered by the laser Q switch, which occurs simultaneously with the simulated AE. In equation (1), the dependent

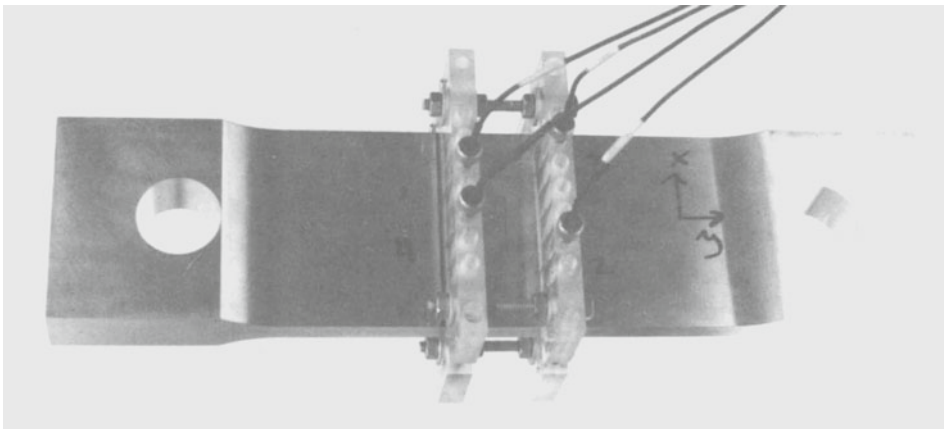


Fig. 1. Aluminum surface-crack specimen used in the tensile test experiments showing the transducers mounted on one side.

variable, T_A , is a function of the independent variables x_o , y_o , and z_o ; the known source coordinates; and of the unknown parameters x_A , y_A , and z_A , the transducer coordinates. A nonlinear least-squares curve fitting program [4] finds the best values of the transducer coordinates that fit the 47 data points. This process is repeated for each transducer.

In the fitting process, the value of the z coordinate of the transducers is actually assumed to be a constant value of either 0.0 (on the surface with the crack) or 12.83 mm (on the back surface). Thus the curve fit involves finding the values of only two parameters: the position relative to the center of the crack in the crack direction (x), and the distance from the plane of the crack (y) (Fig. 2). The results determine the transducer positions with fitting errors of 0.03 to 0.07 mm.

SOURCE LOCATION CAPABILITY

Equation (1) cannot be used for source location because the time of the source is not known. The equations can be rewritten by subtracting T_R from both sides of each equation, where T_R is the time of the longitudinal wave arrival in the reference channel. Then, the signal arrival time of channel A relative to the reference channel, t_A , is:

$$t_A = T_A - T_R$$

$$= [(x_o - x_A)^2 + (y_o - y_A)^2 + (z_o - z_A)^2]^{1/2}/c - T_R$$

In this case the dependent variable is the measured time of arrival of the longitudinal wave at the various transducer locations. The independent variables are the known transducer locations, x_A , y_A , and z_A . The unknown parameters to be determined by the nonlinear least-squares program are the source locations - x_o , y_o , and z_o - and the relative time, T_R .

As a test of the capability of the system to measure source locations, the laser was used to generate simulated AE at known locations. Again 47 sources were generated, but the system is triggered off the signal from one of the channels rather than the laser Q switch.

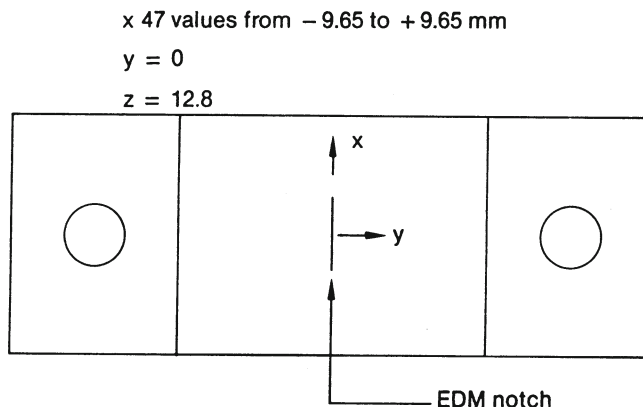


Fig. 2. Experimental setup for test of source location capability.

In addition, the gain of the amplifiers was reduced so that the arriving signals were similar to those expected from actual AE during the tensile tests.

Table 1 shows the results of the test. The average value of x and y should be zero, but the listed values vary from zero due to mispositioning the specimen when setting up the experiment. This systematic error can be expected in the transducer calibration experiment described above. The average and maximum errors are worst for the z coordinate of the source. This may be due to the fact that the z coordinate is fixed in the transducer location fit, but electronic delay differences among the channels may require that the effective z position of the transducers be varied from the actual physical value. The best straightline fit to a plot of the measured source position versus the actual source position has a y intercept of 0.028 ± 0.023 mm and a slope of 1.000 ± 0.006 mm.

AUTOMATED SOURCE LOCATION

Because of the potentially large amount of AE data that can be collected during a fracture test, methods that automatically analyze the data are necessary. For the data described above, the longitudinal wave arrival was originally determined by plotting each channel for each event and using a cursor to locate the arrival. The arrival time was then manually entered into a file for input into the nonlinear least-squares fitting program. Because of the tediousness of that task, only ten of the 47 locations were originally used to determine the transducer locations. Thus 80 manual determinations of longitudinal wave arrivals were made. (The results in Table 1 are derived from 46 of the 47 events in both the transducer location and the source location tests.)

The method used in the manual mode is a model for a program to determine the arrival times automatically. Fig. 3 shows an expanded view of the wave form at the longitudinal wave arrival time. Before the wave arrival some small amount of noise is observed, but the arrival can be distinguished by the large deviation from that noise. The algorithm calculates the average value and the standard deviation of the signal in a moving window of ten points. The arrival time is determined when both of the next two points past the window are more than three standard deviations from the average in the window. Otherwise the window is moved to later time by one point. The actual arrival time is taken to be the last point in the window.

In several cases the algorithm arrival time differed from the manually selected arrival time. Each time this was due to an error in the manual result. For example, using data in Fig. 3, three different persons picked the point labeled 'A' as the first point after the beginning of the signal. The program picked the next point 'B'. This is because point A is still within three standard deviations of the average

TABLE 1. Results of the Source Location Test in mm

	<u>X</u>	<u>Y</u>	<u>Z</u>
Average	0.03	-0.004	12.73
Average Error	0.13	0.08	0.27
Maximum Error	0.32	0.26	1.03

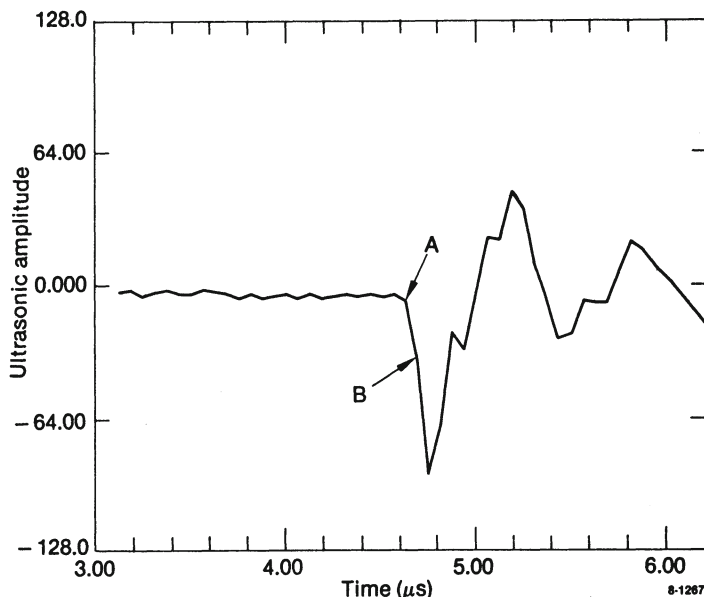


Fig. 3. Expanded view of the longitudinal wave arrival signal.

of the previous ten points, but to the human, point A seems to be the first point after arrival of the longitudinal wave because its deviation from the average is in the same direction as the next point, which is obviously beyond the noise.

Two versions of the automated analysis program are available. The first is used in the transducer location analysis. The arrival times for a given transducer for all the source positions are determined and sent to the least-squares fitting routine, which calculates the transducer location. The program checks for any inaccurate times by comparing the measured arrival times with those calculated using the best-fit values of the transducer-location coordinates. If any time is more than two sampling periods off, it is discarded and the fitting procedure repeated. In the calibration procedure described above, only four times are discarded out of a total of 376 times (8 transducers times 47 sources) determined by the arrival time algorithm.

The second program is used in the source location analysis. Here the arrival times at all the transducers for a given event are determined and input to the least-squares fitting routine and the source locations are returned. Because only eight times are used in the fit, an inaccurate time can invalidate the fit. Thus several of the times would be more than two sampling periods off from those calculated using the best fit and the inaccurate time is not easily identified. To remove the effect of the inaccurate time, the first channel is eliminated from the data and the fitting procedure and test are repeated. This process is then continued until all the times of the remaining channels are in agreement with the calculated results to within two sampling periods. If no consistency is reached after eliminating each of the eight channels, one at a time, the channels are eliminated two at a time. After that the algorithm is considered to have failed. This occurred one time in the source location test described above, and only 46 of the 47 sources are considered in the data in Table 1.

ALUMINUM FRACTURE EXPERIMENT

A 2124 T4 aluminum specimen 12.83 mm thick and 102 mm wide (Fig. 1) was placed in a tensile test machine and pulled to a load of 85,000 lb. The specimen had a surface crack that had been started with an EDM notch and then fatigued until it was nominally 40 mm long and 7 mm deep at the center. During this test the threshold is set relatively low so that a large number of events are observed (161 events). Most of these were due to electrical noise or acoustic noise from the grips. This is determined by looking at the shape and relative arrival times of the signals - electrical noise from the tensile test machine has a distinct shape and identical arrival times, while grip noise is generally of very low amplitude and has nearly identical arrival times.

The automatic source location method is used on all the events, and the results for the 22 events which had reasonable source locations are shown in Fig. 4. Most of the points are clustered between 7 and 10 mm below the top surface of the specimen, in good qualitative agreement with the expected position of the crack tip. Most of these events are within 1 mm of the plane of the crack (y direction), with a maximum deviation of 3 mm. The other events at greater depths are likely due to fractured inclusions in front of the plastic zone ahead of the crack. Such events have been previously observed by Ohira and Pao [5].

In evaluating the data, the algorithm correctly identified about 75% of the actual AE events from the crack area. The method failed for only seven events that have relative delays and shapes similar to the events shown in Fig. 4. All the other events are clearly due to electrical or grip noise.

FUTURE WORK

Several nondestructive tests will be performed to determine the crack extension, and then a destructive analysis will be made in an attempt to identify the sources of AE events observed and measure their actual positions. Another effort will be to identify the nature of the

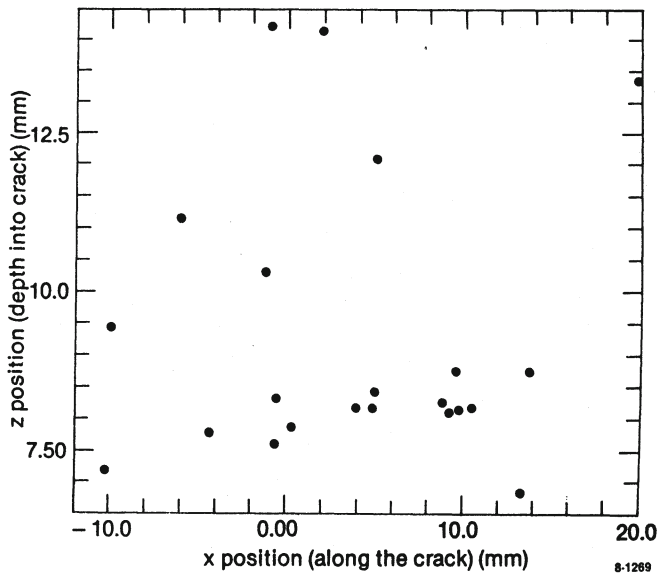


Fig. 4. Location of measured sources projected onto the crack plane.

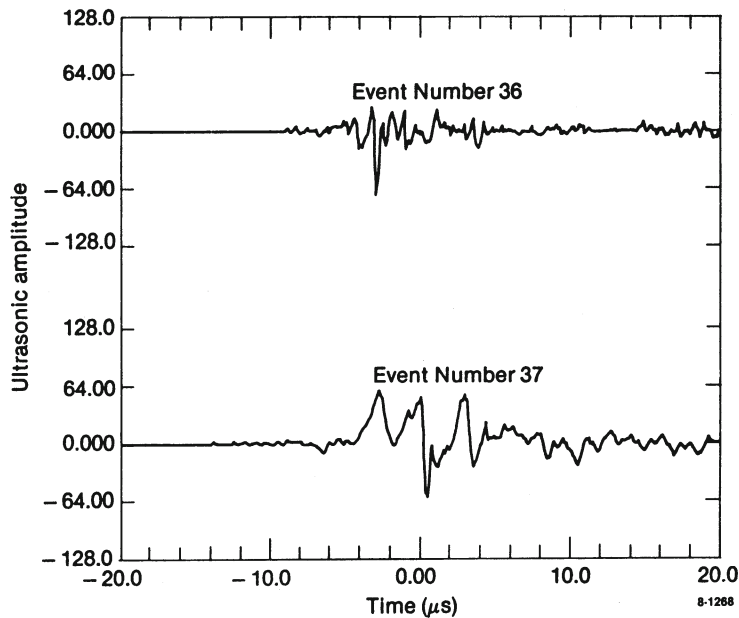


Fig. 5. AE events of different character from the same aluminum specimen.

source of the emissions. For example, the acoustic signature of the ductile tearing which occurs during macrocrack extension is expected to be quite different from that of the microcracking ahead of the plastic zone [5]. Fig. 5 shows two events which occurred in sequence just before catastrophic failure in a different aluminum specimen. These events have clearly different characters; the first contains much higher frequency components than the second.

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